

Methodology and software platform for multi-layer causal modeling

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ABSTRACT: This paper introduces an integrated framework and software platform that uses a three layer approach to modeling complex systems. The multi-layer PRA approach implemented in IRIS (Integrated Risk Information System) combines the power of Event Sequence Diagrams and Fault Trees for modeling risk scenarios and system risks and hazards, with the flexibility of Bayesian Belief Networks for modeling non-deterministic system components (e.g. human, organizational). The three types of models combined in the IRIS integrated framework form a Hybrid Causal Logic (HCL) model that addresses deterministic and probabilistic elements of systems and quantitatively integrates system dependencies. This paper will describe the HCL algorithm and its implementation in IRIS by use of an example from aviation risk assessment (a risk scenario model of aircraft taking off from the wrong runway).

1 INTRODUCTION

Conventional Probabilistic Risk Assessment (PRA) methods model deterministic relations between basic events that combine to form a risk scenario. This is accomplished by using Boolean logic methods, such as Fault Trees (FTs) and Event Trees (ETs) or Event Sequence Diagrams (ESDs). However since with human and organizational failures are among the most important roots of many accidents and incidents, there is an increased interest in expanding causal models to incorporate non-deterministic causal links encountered in human reliability and organizational theory. Bayesian Belief Networks (BBNs) have the capability to model these soft relationships.

This paper describes a new risk methodology known as Hybrid Causal Logic (HCL) that combines the Boolean logic-based PRA methods (ESDs, FTs) with BBNs. The methodology is implemented in a software package called the Integrated Risk Information System (IRIS). The HCL computational engine of IRIS can also be used as a standalone console application. The functionality of this computational engine can be accessed by other applications through an API. IRIS was designed for the United States Federal Aviation Administration. Additional information on IRIS can be found in the references (Groth, Zhu & Mosleh 2008; Zhu et al 2008; Groth 2007).

In this modeling framework risk scenarios are modeled in the top layer using Event Sequence Diagrams. In the second layer, Fault Trees are used to model the factors contributing to the properties and behaviors of the physical system (hardware, software, and environmental factors). Bayesian Belief Networks comprise the third layer to extend the causal chain of events to potential human, organizational, and socio-technical roots.

This approach can be used as the foundation for addressing many of the issues that are commonly encountered in risk and safety analysis and hazard identification. As a causal model, the methodology provides a vehicle for identification and analysis of cause-effect relationships across many different modeling domains, including human, software, hardware, and environment.

The IRIS framework can be used to identify all risk scenarios and contributing events and calculate associated probabilities; to identify the risk value of specific changes and the risk importance of certain elements; and to monitor system risk indicators by considering the frequency of observation and the risk significance over a period of time. Highlighting, trace, and drill down functions are provided to facilitate hazard identification and navigation through the models.

All of the features in IRIS can be implemented with respect to one risk scenario or multiple scenarios, e.g., all of the scenarios leading to a particular category or type of end state. IRIS can be used to

build a single one-layer model, or a network of multi-layer models.

IRIS was developed as part of an international research effort sponsored by the FAA System Approach for Safety Oversight (SASO) office. Other parts of this research created ESDs, FTs, and BBNs by teams of aviation experts from the United States and Europe. IRIS integrates the different models into a standard framework and the HCL algorithm combines quantitative information from the models to calculate total risk.

The Dutch National Aerospace Laboratory (NLR) used the NLR air safety database and aviation experts to create a hierarchical set of 31 generic ESDs representing the possible accident scenarios from takeoff to landing (Roelen et al. 2002)

Another layer of the aviation safety model was created by Hi-Tec Systems. Hi-Tec created a comprehensive model for the quality of air carrier maintenance (Eghbali 2006) and the flight operations (Mandelapu 2006). NLR has also created FTs for specific accident scenarios (Roelen & Wever 2004a, b).

The NLR and Hi-Tec models were built and analyzed in IRIS. One set of models pertains to the use of the incorrect runway during takeoff. These models became especially pertinent after the August 2006 fatal Comair Flight 5191 crash in Lexington, Kentucky. The pilot of flight 5191 taxied onto the wrong runway during an early morning takeoff due to a combination of human and airport factors. The incorrect runway was shorter than the minimum distance required for the aircraft to takeoff. The aircraft was less than 300ft from the end of the runway before pilots realized the error and attempted to takeoff at below-optimal speed. The attempted takeoff resulted in a runway overrun and the death of 49 of the 50 people onboard.

The NTSB (2007) cited human actions by crew and air traffic control (ATC) contributing to the accident. The crew violated cockpit policy by engaging in non-pertinent conversation during taxiing and by completing an abbreviated taxi briefing. Signs indicating the runway number and cockpit displays indicating the direction of takeoff were not mentioned by either pilot during the takeoff. During takeoff the flight crew noted that there were no lights on the runway as expected, but did not double check their position as the copilot had observed numerous lights out on the correct runway the previous day. Pre-flight paperwork also indicated that the center-line lights on the proper runway were out. The flight crew did not use the available cues to reconsider takeoff.

At the time of the accident only one of two required air traffic controllers were on duty. According to post-accident statements, the controller on duty at the time of the accident was also responsible for monitoring radar and was not aware that the air-

craft had stopped short of the desired runway before he issued takeoff clearance. After issuing takeoff clearance the controller turned around to perform administrative tasks during take-off and was not engaged in monitoring the progress of the flight. Fatigue likely contributed to the performance of the controller as he had only slept for 2 hours in the 24 hours before the accident.

Impaired decision making and inappropriate task prioritization by both crew members and ATC were major contributing factors to this accident. The reducing lighting on both the correct and incorrect runways at the airport contributed to the decision errors made by crew and fatigue and workload contributed to decision errors made by ATC. The details from the flight 5191 and the group of models for use of the incorrect runway during takeoff will be used throughout this paper to show how the HCL methodology can be applied to a real example.

2 OVERVIEW OF HCL METHODOLOGY

2.1 Overview of the HCL modeling layers

The hybrid causal logic methodology extends conventional deterministic risk analysis techniques to include “soft” factors including the organizational and regulatory environment of the physical system. The HCL methodology employs a model-based approach to system analysis; this approach can be used as the foundation for addressing many of the issues that are commonly encountered in system safety assessment, hazard identification analysis, and risk analysis. The integrated framework is presented in Figure 1.

ESDs form the top layer of the three layer model, FTs form the second layer, and BBNs form the bottom layer. An ESD is used to model temporal sequences of events. ESDs are similar to event trees and flowcharts; an ESD models the possible paths to

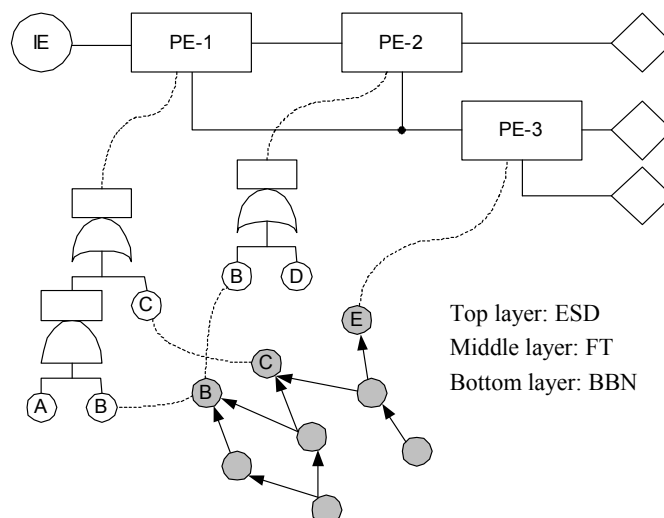
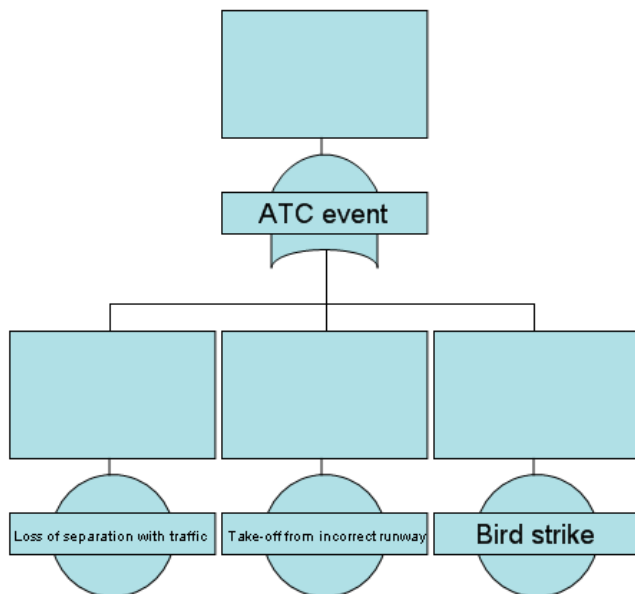
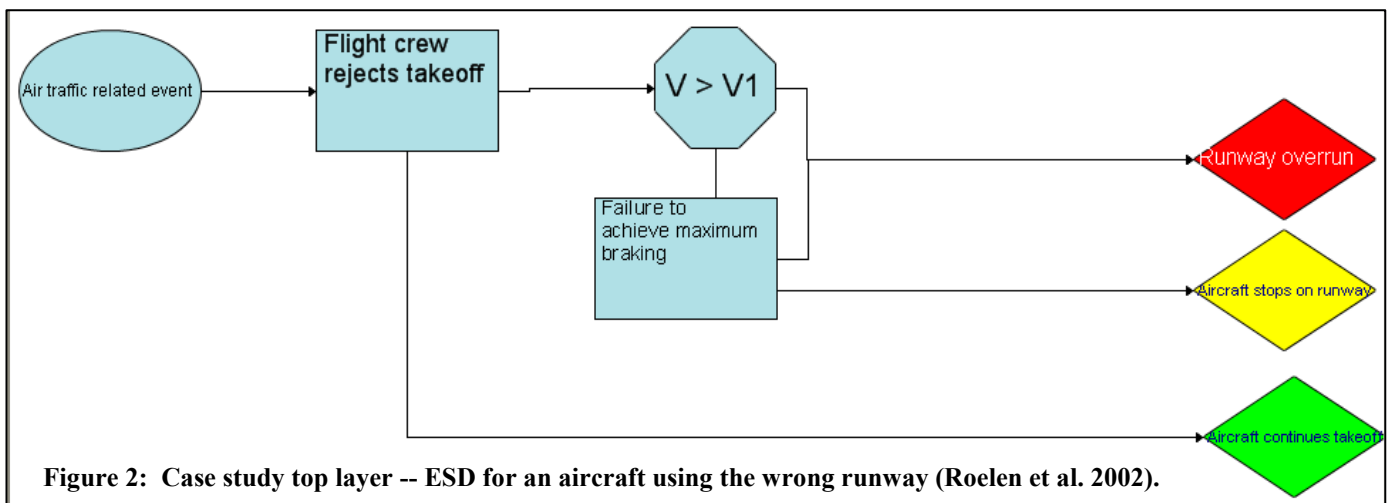


Figure 1: Illustration of a three-layered IRIS model

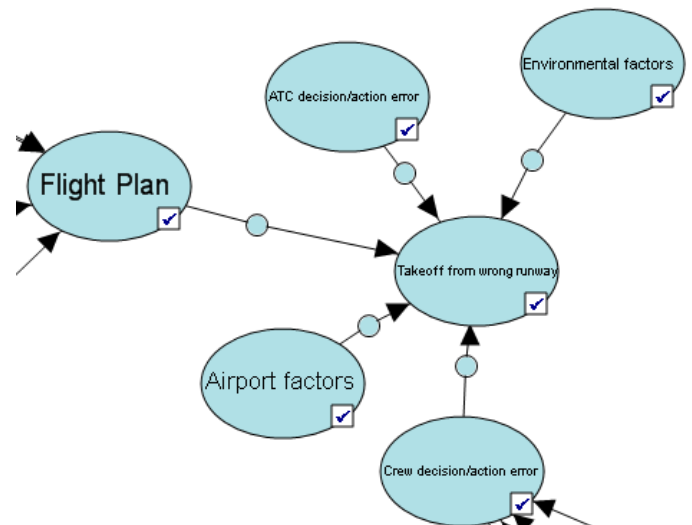


outcomes, each of which could result from the same initiating event. ESDs contain decision nodes where the paths diverge based on the state of a system element. As part of the hybrid causal analysis, the ESDs define the context or base scenarios for the hazards, sources of risk, and safety issues.

The ESD shown in Figure 2 models the probability of an aircraft taking off safely, stopping on the runway, or overrunning the runway. As can be seen in the model, the crew must reject the takeoff and the speed of the aircraft must be lower than the critical speed beyond which the aircraft cannot stop before the end of the runway. By the time the Flight 5191 crew realized the mistake, the plane was above critical speed and the runway overrun was inevitable.

The initiating event of the ESD, *ATC event*, is directly linked to the top gate of the FT in Figure 3. This FT provides three reasons an aircraft could be placed in this situation: *loss of separation with traffic*, *takeoff from incorrect runway*, or a *bird strike*.

FTs use logical relationships (AND, OR, NOT, etc.) to model the physical behaviors of the system. In an HCL model, the top event of a FT can be con-



nected to any event in the ESD. This essentially decomposes the ESD event into a set of physical elements affecting the state of the event, with the node in the ESD taking its probability value from the FT.

BBNs have been added as the third layer of the model. A BBN is a directed acyclic graph, i.e. it cannot contain feedback loops. Directed arcs form paths of influence between variables (nodes). The addition of BBNs to the traditional PRA modeling techniques extends conventional risk analysis by capturing the diversity and complexity of hazards in modern systems. BBNs can be used to model non-deterministic casual factors such as human, environmental and organizational factors.

BBNs offer the capability to deal with sequential dependency and uncertain knowledge. BBNs can be connected to events in ESDs and FTs. The connections between the BBNs and logic models are formed by binary variables in the BBN; the probability of the linked BBN node is then assigned to the ESD or FT event.

The wrong runway event in the center of the FT is the root cause of the accident. Factors that contri-

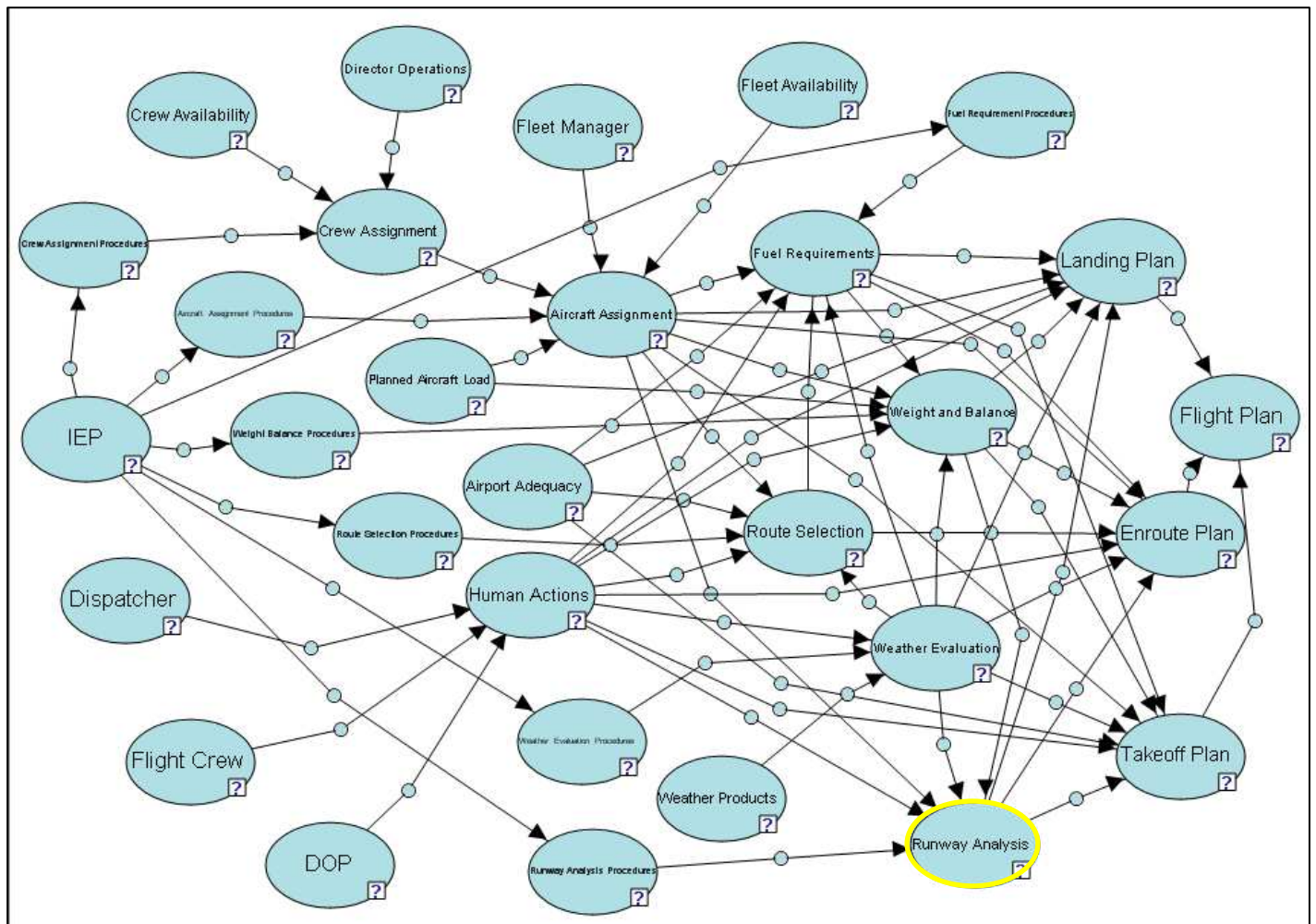


Figure 5: Case study bottom layer -- BBN of flight operations (Mandelapu 2006)

bute to this root cause are modeled in the BBNs in Figure and Figure . Figure is part of the wrong runway BBN developed by NLR (Roelen and Wever 2007); the wrong runway FT event is linked to the output node of this BBN. The *flight plan* node in Figure feeds into the wrong runway node in Figure . Figure is fed by the Hi-Tec air carrier maintenance model (Eghbali 2006; not pictured) with the end node of the maintenance model feeding information into the *fleet availability* node at the top of the flight operations model.

Since many of the casual factors in BBNs may have widespread influence, BBN nodes may impact multiple events within ESDs and FTs. The details of the HCL quantification procedure can be found in the references (Groen & Mosleh 2008, Wang 2007).

2.2 Overview of HCL algorithm quantitative capabilities

An ESD event can be quantified directly by inputting a probability value for the event, or indirectly by linking it to a FT or a node in a BBN. Linked ESD events take on the probability value of the FT or node attached to it. This allows the analyst to set a variable probability for ESD events based on contributing factors from lower layers of the model.

Likewise, FT basic events can be quantified directly or linked to any node in the BBN.

BBN nodes are quantified in conditional probability tables. The size of the conditional probability table for each node depends on the number of parent nodes leading into it. The conditional probability table requires the analyst to provide a probability value for each state of the child node based on every possible combination of the states of parent nodes. The default number of states for a BBN node is 2, although additional states can be added as long as the probability of all states sums to 1. Assuming the child and its n parent nodes all have 2 states, this requires 2^n probability values.

In order to quantify the hybrid model it is necessary to convert the three types of diagrams into a set of models that can communicate mathematically. This is accomplished by converting the ESDs and FTs into Reduced Ordered Binary Decision Diagrams (BDDs). The set of reduced ordered BDDs for a model are all unique and the order of variables along each path from root node to end node is identical. Details on the algorithms used to convert ESDs and FTs into BDDs have been described extensively (Bryant 1992, Brace et al. 1990, Rauzy 1993, Andrews & Dunnett 2000, Groen et al. 2005).

Cut Sets

Importance Measure

Scenario Ranking View

| Ranking | Scenario | End State Type | Severity | Probability | Cut-Sets |
|---------|--|----------------|----------|-------------|----------|
| 1 | Air traffic related event:Runway overrun | Catastrophic | 0 | 2.536E-11 | 6 |
| 2 | Air traffic related event:Aircraft stops on | Of concern | 0 | 6.533E-8 | 3 |
| 3 | Air traffic related event:Aircraft continues takeoff | | 0 | 6.168E-7 | 3 |

Cut Set View

| Ranking | Events | Probability | Scenario |
|---------|--|-------------|--|
| 1 | Take-off from incorrect runway"Flight crew rejects takeoff"> V1 | 1.758E-11 | Air traffic related event:Runway overrun |
| 2 | Take-off from incorrect runway"Flight crew rejects takeoff"Failure to | 6.779E-12 | Air traffic related event:Runway overrun |
| 3 | loss of separation with traffic on other runway/airborne"Flight crew r | 6.465E-13 | Air traffic related event:Runway overrun |
| 4 | loss of separation with traffic on other runway/airborne"Flight crew r | 2.493E-13 | Air traffic related event:Runway overrun |
| 5 | bird strike"Flight crew rejects takeoff"> V1 | 7.725E-14 | Air traffic related event:Runway overrun |
| 6 | bird strike"Flight crew rejects takeoff"Failure to achieve maximum br | 2.980E-14 | Air traffic related event:Runway overrun |

Figure 6: Probability values and cut sets for the base wrong runway scenario.

BBNs are not converted into BDDs; instead, a hybrid BDD/BBN is created. In this hybrid structure, the probability of one or more of the BDD variables is provided by a linked node in the BBN. Additional details about the BDD/BBN link can be found in Groen & Mosleh (2008).

3 HCL-BASED RISK MANAGEMENT METRICS

In addition to providing probability values for each ESD scenario, each FT and each BBN node, the HCL methodology provides functions for tracking risks over time and for determining the elements that contribute most to scenario risk. HCL also provides the minimal cut-sets for each ESD scenario, allowing the user to rank the risk scenarios quantitatively. Specific functions are described in more detail below. For additional technical details see (Mosleh et al. 2007).

Figure 7 displays scenario results for the wrong runway scenario. It is clear that the most probable outcome of using the wrong runway is a continued takeoff with no consequences. The bottom half of the figure displays the cut-sets only for the scenarios that end with a runway overrun. As can be seen in the figure, the most likely series of event reading to an overrun is the combination of using the incorrect runway, attempting a rejected takeoff, and having speed in excess of the critical stopping speed (V1). This is the pattern displayed by flight 5191.

3.1 Importance Measures

Importance measures are used to identify the most significant contributors to a risk scenario. They provide a quantitative way to identify the most important system hazards and to understand which model elements most affect system risk. Importance meas-

ures can be used to calculate the amount of additional safety resulting from a system modification, which allows analysts to examine the benefits of different modifications before implementation. Analysts can also use importance measures to identify the elements that most contribute to a risk scenario and then target system changes to maximize the safety impact.

There are numerous ways to calculate importance measures for Boolean models. However, due to the dependencies in HCL models introduced by inclusion of BBNs, the methods cannot be applied in their original form. Four conventional importance measures have been modified and implemented in HCL: Risk Achievement Work (RAW), Risk Reduction Worth (RRW), Birnbaum, and Vesely-Fussel (VF).

The standard Vesely-Fussel importance measure (Eq. 1) calculates the probability that event e has occurred given that ESD end state S has occurred (Fussel 1975).

$$p(e | S) = \frac{p(e \cdot S)}{P(S)} \quad (1)$$

For hybrid models, event e is a given state of a model element, e.g. a FT event is failed or a BBN node is "degraded" instead of "fully functional" or "failed." By addressing a particular state, it is possible to extend importance measures to all layers of the hybrid model.

Importance measures must be calculated with respect to an ESD end state. To ensure independence in ESDs with multiple paths, it is necessary to treat the end state S as the sum of the S_i mutually exclusive paths leading to it. The importance measure can then be calculated by using Equation 2.

$$p(S) = \frac{\sum_i p(e \cdot S_i)}{\sum_i p(S_i)} = \frac{\sum_i p(S_i | e)}{\sum_i p(S_i)} \quad (2)$$

| Cut Sets Importance Measure | | | | |
|------------------------------------|--|--|-------------|----------------|
| Highlight based on: | | End State: | No Category | Percentage: 10 |
| Importance Measure View - Scenario | | | | |
| Index | Scenario | Component | RAW | Vesely-Fussel |
| 1 | Air traffic related event:Runway overrun | Take-off from incorrect runway | 1.466E6 | 9.605E-1 |
| 2 | Air traffic related event:Runway overrun | Flight Crew:Unsafe | 1.000E0 | 5.000E-1 |
| 3 | Air traffic related event:Runway overrun | Human Actions:Unsafe | 1.010E0 | 5.729E-2 |
| 4 | Air traffic related event:Runway overrun | loss of separation with traffic on other runway/airborne | 1.466E6 | 3.533E-2 |
| 5 | Air traffic related event:Runway overrun | Airport Adequacy:Substandard | 1.006E0 | 2.355E-2 |
| 6 | Air traffic related event:Runway overrun | Runway Analysis Procedures:Substandard | 9.999E-1 | 2.118E-2 |

Figure 7: Importance measure results for the runway overrun model.

For a set of scenarios belonging to two or more ESDs the probability can be calculated as a function of the results from each ESD or by use of the mean upper bound approximation. Additional details on HCL importance measure calculations can be found in Zhu (2008).

Figure 7 provides importance measure results for the runway overrun model. The importance measures in the figure are arranged by the Vesely-Fussel importance measure. The items in the components column are FT events and some selected BBN nodes. The BBN nodes selected reflect the factors that contributed to the runway overrun of Flight 5191. From the figure it is obvious that *take-off from incorrect runway* is the most important contributing factor to the runway overrun end state.

3.2 Risk indicators

Risk indicators are used to identify potential system risks by considering both the risk significance and the frequency of the event. They are also used to monitor system risks and to track changes in risk over time. Risk significance is calculated with respect to selected ESD scenarios or end states. It can be calculated for any BBN node, FT gate or event, or ESD pivotal event.

The risk indicator is calculated by Equation 3, where R is the total risk, ϕ is the frequency of the event.

$$R = \Pr(S | f) \cdot \phi \quad (3)$$

$\Pr(S|f)$ is the risk weight of a BBN node or FT event or gate (f) and S is the selected ESD end state or group of end states. If S consists of an end state category or multiple end states in the same ESD Equation 3 is modified using the same logic explained for modifying Equation 1. For multiple end states in different ESDs the risk indicator value can be calculated using the upper bound approximation. The procedure for performing precursor analysis and ha-

zard ranking follows directly from the risk indicator procedure.

Figure 8 displays individual risk indicators and total risk for several BBN nodes from the example model. Frequency values are to be provided by the analyst. In the example case, the frequency values were selected to show how IRIS could be used to monitor the risks before the accident; these are not values from data. The top graph in Figure 8 shows the changing risk values for each of the three selected indicators. The bottom graph shows the aggregated risk value over time. Based on the risk values obtained from the models and the hypothetical frequency data, it becomes apparent that the risk associated with airport adequacy increased sharply between May and July. The hypothetical risks associated with the adequacy of the airport could have been identified in July and steps could have been taken to reduce these risks before serious consequences occurred.

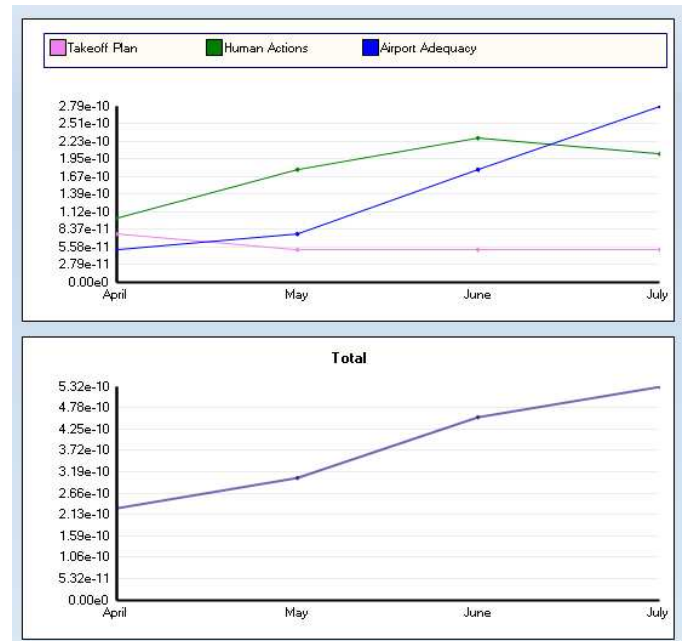


Figure 8: Sample risk indicators implemented in IRIS

| Cut Sets Importance Measure | | | | | |
|-----------------------------|--|----------------|----------|-------------|----------|
| Scenario Ranking View | | | | | |
| Ranking | Scenario | End State Type | Severity | Probability | Cut-Sets |
| 1 | Air traffic related event:Runway overrun | Catastrophic | 0 | 8.893E-10 | 6 |
| 2 | Air traffic related event:Aircraft stops on | Of concern | 0 | 2.291E-6 | 3 |
| 3 | Air traffic related event:Aircraft continues | Safe | 0 | 2.190E-5 | 3 |

| Cut Set View | | | |
|--------------|--|-------------|--|
| Ranking | Events | Probability | Scenario |
| 1 | Take-off from incorrect runway*Flight crew rejects takeoff*V > V1 | 6.411E-10 | Air traffic related event:Runway overrun |
| 2 | Take-off from incorrect runway*Flight crew rejects takeoff*Failure to | 2.473E-10 | Air traffic related event:Runway overrun |
| 3 | loss of separation with traffic on other runway/airborne*Flight crew r | 6.465E-13 | Air traffic related event:Runway overrun |
| 4 | loss of separation with traffic on other runway/airborne*Flight crew r | 2.493E-13 | Air traffic related event:Runway overrun |
| 5 | bird strike*Flight crew rejects takeoff*V > V1 | 7.725E-14 | Air traffic related event:Runway overrun |
| 6 | bird strike*Flight crew rejects takeoff*Failure to achieve maximum b | 2.980E-14 | Air traffic related event:Runway overrun |
| 7 | Take-off from incorrect runway*Flight crew rejects takeoff | 2.290E-6 | Air traffic related event:Aircraft stops on runway |

Figure 9: Updated scenario results for the runway overrun with information about flight 5191 specified.

3.3 Risk impact

Analysts can use IRIS to visualize the change in system risk based on observed or postulated conditions. This can be achieved by using the set evidence function to make assumptions about the state of one or more BBN nodes. Once assumptions are made the model is updated to reflect the new information, providing new probability values for all nodes subsequently affected by the changes.

When the BBN is linked to an ESD or FT, the new ESD and FT models will also display new probability values. The set evidence function allows users to see the impact of soft factors on risk scenarios. The result is a more tangible link between the actions of humans/organizations and specific system outcomes.

Setting evidence will provide users with a better understanding of how low-level problems propagate through the system and combine to form risk scenarios. Figure 9 displays updated scenario results for the flight 5191 overrun. In this scenario, evidence was set for three nodes in the BBN (Fig.Figure). Human actions was set to the state unsafe because of errors made by the flight 5191 flight crew. Airport adequacy was set to the state inadequate because of

the lack of proper lighting on both runways. The takeoff plan was deemed substandard.

By comparing the results of the base case, Figure 6, to the case updated with scenario evidence, Figure 9, it is possible to quantify the change in risk accompany certain behaviors. The updated probability of a runway overrun based on human actions, airport conditions, and the takeoff plan is an order of magnitude greater than the probability of the base scenario. Again, the series of events leading to the flight 5191 crash is the most probable sequence leading to an overrun in the model.

It is evident from Figure 10 that the three BBN nodes strongly impact the probability of taking off from the incorrect runway. This probability increases by almost a factor of 2 when the model is updated with the scenario evidence.

CONCLUSION

This paper provides an overview of the hybrid causal logic (HCL) methodology for Probabilistic Risk Assessment and the IRIS software package developed to use the HCL methodology for comprehensive risk analyses of complex systems. The HCL methodology and the associated computational en-

| Minimum Cuts and Probability: | | |
|-------------------------------|--|-------------|
| Ranking | Minimal Cut | Probability |
| 1 | Take-off from incorrect runway | 6.552E-7 |
| 2 | loss of separation with traffic on other runway/airborne | 2.410E-8 |
| 3 | bird strike | 2.880E-9 |

| Minimum Cuts and Probability: | | |
|-------------------------------|--|-------------|
| Ranking | Minimal Cut | Probability |
| 1 | Take-off from incorrect runway | 2.419E-5 |
| 2 | loss of separation with traffic on other runway/airborne | 2.410E-8 |
| 3 | bird strike | 2.880E-9 |

Figure 10: Fault tree results showing the probability of taking off from the wrong runway for the base case (top) and the case reflecting flight 5191 factors (bottom).

gine were designed to be portable and thus there is no specific HCL GUI. The computational engine can read models from files and can be accessed through use of an API.

The three-layer The flexible nature of the HCL framework allows a wide range of GUIs to be developed for many industries. The IRIS package is designed to be used by PRA experts and systems analysts. Additional GUIs can be added to allow users outside of the PRA community to use IRIS without in depth knowledge of the modeling concepts and all of the analysis tool.

Two FAA specific GUIs were designed with two different target users in mind. Target users provided information about what information they needed from IRIS and how they would like to see it presented. The GUIs were linked to specific IRIS analysis tools, but enabled the results to be presented in a more qualitative (e.g. high/medium/low) way.

The GUIs were designed to allow target users to operate the software immediately. Users are also able to view underlying models and see full quantitative results if desired.

HCL framework was applied to the flight 5191 runway overrun event from 2006, and the event was analyzed based on information obtained about the conditions contributing to the accident.

The three layer HCL framework allows different modeling techniques to be used for different aspects of a system. The hybrid framework goes beyond typical PRA methods to permit the inclusion of soft causal factors introduced by human and organizational aspects of a system. The hybrid models and IRIS software package provide a framework for unifying multiple aspects of complex socio-technological systems to perform system safety analysis, hazard analysis and risk analysis.

The methodology can be used to identify the most important system elements that contribute to specific outcomes and provides decision makers with a quantitative basis for allocating resources and making changes to any part of a system.

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